

Exposure of Tropical Ecosystems to Artificial Light at Night:

Brazil as a Case Study

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14 **Abstract**

15 Artificial nighttime lighting from streetlights and other sources has a broad range of biological effects.
16 Understanding the spatial and temporal levels and patterns of this lighting is a key step in determining
17 the severity of adverse effects on different ecosystems, vegetation, and habitat types. Few such
18 analyses have been conducted, particularly for regions with high biodiversity, including the tropics.
19 We used an intercalibrated version of the Defense Meteorological Satellite Program's Operational
20 Linescan System (DMSP/OLS) images of stable nighttime lights to determine what proportion of
21 original and current Brazilian vegetation types are experiencing measurable levels of artificial light
22 and how this has changed in recent years. The percentage area affected by both detectable light and
23 increases in brightness ranged between 0 and 35% for native vegetation types, and between 0 and
24 25% for current vegetation (i.e. including agriculture). The most heavily affected areas encompassed
25 terrestrial coastal vegetation types (restingas and mangroves), Semideciduous Seasonal Forest, and
26 Mixed Ombrophilous Forest. The existing small remnants of Lowland Deciduous and Semideciduous
27 Seasonal Forests and of Campinarana had the lowest exposure levels to artificial light. Light pollution
28 has not often been investigated in developing countries but our data show that it is an environmental
29 concern.

31 **Introduction**

32 The nighttime environment is undergoing a dramatic transformation across the Earth's
33 surface. The cycles of natural light (daily, lunar and seasonal) that have been major forms of
34 environmental variation since the first emergence of life are being disrupted through the introduction
35 of artificial lighting. A diversity of sources (including street lighting, advertising lighting,
36 architectural lighting, security lighting, domestic lighting and vehicle lighting) are causing direct
37 illumination as well as via skyglow, the scattering by atmospheric molecules or aerosols of artificial
38 light at night that is emitted or reflected upwards [1–5].

39 Because natural cycles of light have previously provided rather consistent resources and
40 sources of information for organisms, artificial nighttime lighting has a broad range of biological
41 effects [5–7]. These span from gene to ecosystem levels [8,9]. They include effects on the physiology,
42 behaviour, reproductive success and mortality of species (e.g. 10–13), on their abundance and
43 distribution [14], and in turn on community structures and functioning (e.g. 2,15). Moreover, it seems
44 likely that the impacts of artificial nighttime lighting interact with those of other pressures on
45 biodiversity, including habitat loss, climate change, other forms of pollution, and invasive species
46 [16].

47 Determining the severity of these biological impacts rests, in part, on understanding of the
48 spatial and temporal levels and patterns of artificial nighttime lighting, and particularly how these
49 interact with those of different ecosystem, vegetation and habitat types [16]. At a global scale,
50 virtually all natural terrestrial ecosystem types experience some level of exposure to artificial
51 nighttime lighting or skyglow, and those that have been most and least affected have been identified
52 [4]. However, more detailed regional analyses have largely been wanting. A few evaluations exist of
53 regional patterns of artificial nighttime lighting, but these have not tended to determine the interaction
54 with ecosystem, vegetation, or habitat types (e.g. 15,17). Of particular concern is that work on spatial
55 patterns of artificial nighttime lighting has focussed predominantly on China, Europe and North
56 America [1,3,17,18] with almost no attention to global biodiversity hotspots. In particular, the
57 potential environmental impacts of artificial nighttime lighting in tropical regions have been
58 surprisingly little considered.

59 Aside from the often much greater levels of biodiversity that could be influenced, it remains
60 unknown whether artificial nighttime lighting has different impacts in tropical regions compared
61 with temperate ones. Obvious differences between tropical and non-tropical regions that might be
62 significant are the short and rather invariant tropical periods of twilight, relatively low proportions of
63 crepuscular and cathemeral species in tropical regions [19], the greater specialisation in tropical
64 regions of some interspecific interactions that are known to be susceptible to influences from artificial

65 nighttime light (e.g. plant-pollinator; [20,21]), and the prevalence of terrestrial species using
66 bioluminescence, which are known to be vulnerable to light pollution [22–24].

67 In this paper we determine the spatial and temporal patterns of artificial nighttime lighting
68 across Brazil in relation to the distribution of vegetation types. Brazil makes a particularly valuable
69 case study. As well as being the largest country in South America, it has the largest number of species
70 of any country in the world for many major taxonomic groups [25], has high levels of species
71 endemism, and two recognised global biodiversity hotspots [26]. Brazil also has the richest
72 biodiversity of bioluminescent beetles in the world [27].

73

74 **Methods**

75 **Light Data**

76 Following Bennie *et al.* [3], we used nighttime stable lights annual composite images, created
77 with data from the Defense Meteorological Satellite Program's Operational Linescan System
78 (DMSP/OLS), downloaded from the National Oceanic and Atmospheric Administration archives
79 (1992-2012, $n = 21$). These images capture upwardly reflected and directed nighttime light. The
80 images are nominally at 1 km resolution, but are re-sampled from data at an equal angle of
81 approximately 2.7 km resolution at the equator. These images cover spectral responses from 440 to
82 940 nm with the highest sensitivity in the 500 to 650 nm region. The spectral range encompasses the
83 primary emissions from the most widely used sources for external lighting in Brazil: low pressure
84 sodium (589 nm), high pressure sodium (from 540 nm to 630 nm) and mercury vapour (545 and 575
85 nm) [1,28].

86 Each pixel is represented by a digital number (DN) of between 0 and 63. Zero represents no
87 detectable upward radiance, while brightly lit areas saturate at values of 63. Images were inter-
88 calibrated and drift-corrected following the method of Bennie *et al.* [3]. An average calibrated image
89 for both the first (1992–1996) and the last (2008–2012) five years was created and the difference was
90 calculated. To assess the changes over the full period time, we considered pixels increasing or

decreasing by more than a threshold of 3 DN units of difference between the averages of the first and last years. It was previously observed that over 94% of observed increases in DN of more than 3 units and over 93% of observed decreases of the same magnitude were consistently related to the directions of changes on the ground (e.g., expansion or contraction of urban and industrial areas) [3]. Following Gaston *et al.* [29] and Duffy *et al.* [30], we considered pixels as exposed to artificial light when they had values higher than 5.5 DN units. By using a threshold effectively twice the detection limit for change, we defined a conservative estimate of lit area and limited the extent to which dark sites may be classified as lit due to noise in the data set or calibration errors [29,30].

Vegetation type data

We used the vegetation map produced by the Brazilian Institute for Geography and Statistics [31], which is recommended as a good basis to compare with data obtained from remote sensing images [32]. This map presents both original native vegetation and current vegetation and land cover. The former portrays the original vegetation classes in Brazil likely found at the time of Portuguese colonisation [31], and the latter describes the vegetation now present [31]. Original vegetation includes 24 wider classes while the current is more detailed, including 52 classes (Table 1). The shapefile was produced by IBGE - Brazilian Institute of Geography and Statistics and accessed through REDD-PAC website (http://www.redd-pac.org/new_page.php?contents=data.csv) in WFS (web feature service) format.

Table 1. Vegetation classification for Brazil according to IBGE (2012).

| | | | | |
|--------|---------------------|---------------------------|--|---------------------------------------|
| Forest | Ombrophilous Forest | Dense Ombrophilous Forest | | Alluvial Dense Ombrophilous Forest |
| | | | | Lowland Dense Ombrophilous Forest |
| | | | | Sub-Montane Dense Ombrophilous Forest |
| | | | | Montane Dense Ombrophilous Forest |
| | | Open Ombrophilous Forest | | Alluvial Open Ombrophilous Forest |

| | | | |
|------------|-----------------|---|---|
| | | | Lowland Open Ombrophilous Forest |
| | | | Sub-Montane Open Ombrophilous Forest |
| | | Mixed Ombrophilous Forest | Montane Mixed Ombrophilous Forest |
| | | | High-montane Mixed Ombrophilous Forest |
| | Seasonal Forest | Semi-deciduous Seasonal Forest | Alluvial Semi deciduous Seasonal Forest |
| | | | Lowland Semi deciduous Seasonal Forest |
| | | | Sub-Montane Semi-deciduous Seasonal Forest |
| | | | Montane Semi-deciduous Seasonal Forest |
| | | Deciduous Seasonal Forest | Lowland Deciduous Seasonal Forest |
| | | | Sub-Montane Deciduous Seasonal Forest |
| | | | Montane Deciduous Seasonal Forest |
| Non Forest | | Campinarana | Forest Campinarana |
| | | | Woody Campinarana |
| | | | Shrubland Campinarana |
| | | | Grassland Campinarana |
| | | Savanna | Forest Savanna |
| | | | Woody Savanna |
| | | | Parkland Savanna |
| | | | Grassland Savanna |
| | | Steppe-savanna | Forest Steppe-savanna |
| | | | Woody Steppe-savanna |
| | | | Parkland Steppe-savanna |
| | | | Grassland Steppe-savanna |
| | | Steppe | Woody Steppe |
| | | | Parkland Steppe |
| | | | Grassland Steppe |
| | | Pioneer formation | Alluvial Areas |
| | | | Restinga |
| | | | Mangrove |
| Other | Ecotone | Campinarana/Ombrophilous Forest | Campinarana/Ombrophilous Forest |
| | | Steppe/seasonal Forest | Steppe/seasonal Forest |
| | | Seasonal Forest /Primary Formations | Seasonal Forest /Primary Formations |
| | | Dense Ombrophilous Forest/Mixed Ombrophilous Forest | Dense Ombrophilous Forest/Mixed Ombrophilous Forest |
| | | Ombrophilous Forest/Seasonal Forest | Ombrophilous Forest/Seasonal Forest |
| | | Steppe savanna /Seasonal Forest | Steppe savanna /Seasonal Forest |
| | | Savanna/Seasonal Forest | Savanna/Seasonal Forest |
| | | Savanna/Ombrophilous Forest | Savanna/Ombrophilous Forest |
| | | Savanna/Primary Formations | Savanna/Primary Formations |
| | | Savanna/Steppe-savanna | Savanna/Steppe-savanna |
| | | Savanna/Steppe-savanna/Seasonal | Savanna/Steppe-savanna/Seasonal Forest |

| | | |
|-------------------|-------------------|--------------------------------|
| | Forest | |
| Relict Vegetation | Relict Vegetation | High-montane Relict Vegetation |
| | | Montane Relict Vegetation |
| Water | Water | Coastal Water Mass |
| | | Continental Water Mass |
| Rocky Outcrops | Rocky Outcrops | Rocky Outcrops |
| ----- | | Agriculture |
| | | Secondary Vegetation |

The third column corresponds to original vegetation and the fourth column to current vegetation.

The IBGE map divides vegetation into two broad classes: forests and non-forests [33]. Forests are divided into Ombrophilous Forest and Seasonal Forest. The former is further divided into three physiognomies (Dense, Open and Mixed) and the last into two (Deciduous and Semi-deciduous). All of these can be classified by up to five formations: Alluvial, Lowland, Sub montane, Montane and High-montane (Table 1). Non-forests are divided into four formations: Campinarana, Savanna, Steppe-savanna, and Steppe, which in turn can be divided into up to four formations: Forest, Woody, Shrubland, and Grassland. The map also classifies pioneer formations - that encompass vegetation influenced by rivers (Alluvial Areas), by the sea (Restingas), and by both (Mangroves) - Ecotones, Relict Vegetation and Water. When considering the current vegetation, it also includes Agriculture and Secondary Vegetation classes (Table 1).

Processing

To define the proportional area of each vegetation type that has been exposed to artificial nighttime light, we overlaid both original and current vegetation shapefiles on the DMSP data for the most recent five years (2008-2012). We extracted both the number of lit pixels and the total number of pixels inside each vegetation type and divided the first by the second. To assess changes, we overlaid the two vegetation shapefiles on the difference between the first (1992–1996) and the last (2008–2012) five years of DMSP data. We extracted the number of increasing pixels, decreasing pixels and the total number of pixels inside each vegetation type. We divided the number of increasing

134 and decreasing pixels by the total in each vegetation type, achieving the proportional area where
135 artificial light has been increasing and decreasing respectively.

136

137 Results

138 Overall, the percentage of area of each vegetation type affected by increases in artificial light
139 was higher than the percentages affected by ‘detectable’ light (Figs 1 and 2). Less than 0.00001% of
140 the areas of vegetation types experienced decreases in brightness so we considered only the increases
141 in the results.

142

143 **Figure 1. Percentage of area of original vegetation types affected by artificial light.** Horizontal
144 bars show the percentage of total land surface area occupied by each original vegetation type that had
145 more than 5.5 Digital Number (DN) units in 2008-2012 (red) or an increase of more than 3 DN units
146 between 1992-2012 and 2008-2012 (blue).

147

148

149 **Figure 2. Percentage of area of current vegetation types affected by artificial light.** Horizontal
150 bars show the percentage of total land surface area occupied by each current vegetation type that had
151 more than 5.5 Digital Number (DN) units in 2008-2012 (red) or an increase of more than 3 DN units
152 between 1992-2012 and 2008-2012 (blue).

153

154 Spatial distribution of detectable light and increases in brightness followed similar patterns.

155 The most affected areas were strongly concentrated along the coast, in the east, particularly in the

156 southeast, while less affected areas were located in the west and in the central region (Fig. 3 A-B).

157 **Figure 3. Spatial distribution of artificial light and vegetation types in Brazil.** Distribution of:
158 (A) pixels with detectable light (DN > 5.5) in the most recent five years (2008-2012); (B) pixels with
159 increases in brightness (differences higher than 3 DN) between the first (1992-1998) and the last
160 (2008-2012) five years; (C) original vegetation types; and (D) current vegetation types. The figure
161 was created using QGIS 2.12.3. Nighttime light images were created with data from the Defense
162 Meteorological Satellite Program’s Operational Linescan System (DMSP/OLS), freely available at
163 the website of National Oceanic and Atmospheric Administration/National Geophysical Data Center
164 (NOAA/NGDC) Earth Observation Group (<http://ngdc.noaa.gov/eog/>). The shapefile of Brazilian
165 vegetation types was produced by IBGE (Brazilian Institute of Geography and Statistics) and is freely
166 available at REDD-PAC website (http://www.redd-pac.org/new_page.php?contents=data.csv) in
167 WFS (web feature service) format.

168

169 Pre-colonization native vegetation

170 The area of original vegetation types affected by both detectable light and increases in
171 brightness ranged between 0% and approximately 35%. Types affected by detectable light in more
172 than 10% of their areas include pioneer formations (which encompass Mangroves, Restingas, and
173 Alluvial Areas - Table 1), Semideciduous Seasonal Forest, Mixed Ombrophilous Forest, and six
174 ecotones containing these ones and also Savanna, Steppe-savanna, Dense Ombrophilous Forest, and
175 Steppe (Fig 1).

176 Less than 1% of the areas of three original vegetation types were affected by both detectable
177 light and increases in exposure: Campinarana/Ombrophilous Forest, Savanna/ Pioneer Formations,
178 and Ombrophilous Forest/Seasonal Forest (Fig 1). Two out of 24 original vegetation types had levels
179 of detectable artificial light at night below the threshold: Rocky Outcrops and Campinarana (Fig 1).
180 The less affected original vegetation types were concentrated in the west and in the central area while
181 the most affected were in the southeast and northeast (Fig 3 A, C).

182
183

184 **Current vegetation**

185 The area of current vegetation types affected by detectable light ranged between less than 1%
186 and approximately 25%. Restingas, Mangroves, Secondary Vegetation, and Steppe/Seasonal Forest
187 had more than 10% of their areas affected by detectable light (Fig 2). The first three were also the
188 most affected by changes in brightness as well as Seasonal Forest/ Pioneer Formations (Fig 2).

189 Vegetation types with less than 1% of their areas affected by both detectable light and
190 increases in exposure were the three formations of Open and Dense Ombrophilous Forest (Alluvial,
191 Lowland and Sub-montane - Table 1), Alluvial Semideciduous Seasonal Forest, Sub-Montane
192 Deciduous Seasonal Forest and four ecotones involving Savanna, Ombrophilous Forest, Pioneer
193 Formations (mainly Mangroves and Restingas), Campinarana and Seasonal Forest (Fig 2).

194 100% of the areas of seven of the 52 current vegetation types had levels of detectable artificial
195 light lower than the threshold: Rocky Outcrops, the four formations of Campinarana (i.e. Woody,
196 Shrubland, Forest and Grassland - Table 1), Lowland Deciduous Seasonal Forest and Lowland

197 Semideciduous Seasonal Forest (Fig 2).

198 The most affected current vegetation types were strongly concentrated along the coast, in the
199 east. The less affected ones occurred in the west (where Amazonia rainforest is located) and in the
200 central area (Fig 3 B, D).

201

202 **Discussion**

203 In this paper we provide the first assessment of the broad level of exposure of tropical and
204 subtropical ecosystems to artificial light at night at a regional extent. Because the percentage of areas
205 of the different vegetation types affected by increases in brightness was higher than those affected by
206 detectable light in most of the cases (Figs 1, 2 and 3 A-B), it seems inevitable that the extent of
207 artificial lighting will continue to increase.

208 The highest aggregations of artificial lights in Brazil are in the coastal regions (Fig 3 A-B)
209 from where occupancy of Brazilian territory by Europeans started and where the larger urban
210 agglomerations are now located [34]. The three most widely lit vegetation types when considering
211 original vegetation are ecotones and all of them involve Seasonal Forest or Mixed Ombrophilous
212 Forest (Fig 1). Semideciduous Seasonal Forest and Mixed Ombrophilous Forest themselves are also
213 widely lit by detectable light (16.7% and 13.6% respectively - Fig 1). These levels of coverage by
214 artificial lighting are lower for current vegetation of the same types (6.18% for Montane
215 Semideciduous Forest, 1.2% for Sub-montane Semideciduous Forest, 7.25% for Montane Mixed
216 Ombrophilous Forest, and 3.5% for High-montane Mixed Ombrophilous Forest) because they have
217 been highly converted and the current remnants are small [35]. Of the current vegetation types,
218 Restingas, Mangroves and Coastal water mass are among the five with the greatest percentage
219 coverage by artificial nighttime lighting (Fig 2).

220 Imagery of emissions of upward radiance are the best available data to assess both the presence
221 and trends in artificial light at a regional scale (other artificial nighttime lighting data sets do not yet
222 capture trends). However, as pointed by Bennie *et al.* [4], trends established using these data must be

223 interpreted with caution because the relationships between the images captured by the satellites and
224 biologically relevant levels of light experienced by species are not straightforward. First, the spectral
225 response of the OLS instrument covers the ranges of the most commonly used sources for external
226 light, which differs from the action spectra of biological processes depending on the species. Second,
227 because DMSP/OLS images are approximately at 2.7 km resolution, the correspondence between the
228 illuminated areas in the images and the areas at the ground surface where biologically significant
229 levels of lights are present is not precise. And finally, upwards radiance measures do not encompass
230 horizontal emissions or skyglow – although it is important to observe that empirical data on temporal
231 trends in the spatial occurrence of skyglow at continental scales are not presently available, and
232 modelled surface data have large uncertainties [36,37].

233 Whilst an impressively wide array of ecological impacts of artificial nighttime lighting have
234 been documented (see Introduction), the most important effects on given vegetation types and their
235 associated communities remain unknown. Nonetheless, Semideciduous Seasonal Forest may
236 potentially be differentially impacted because the trees lose from 20% to 50% of their leaves during
237 the unfavourable season (i.e. dry and cold season in tropical and subtropical zones respectively [30])
238 and street lighting has previously been shown in other contexts to affect leaf fall timing as well as the
239 speed of leaf growth [38,39]. Mixed Ombrophilous Forest, also known as araucaria forest due to the
240 dominance of Brazilian pine (*Araucaria angustifolia*) [33], has a notably high richness and diversity
241 of dung beetles [40]. It is known that dung beetles exploit moonlight, the celestial polarization pattern
242 and the starry sky for orientation [41–44]. Given the important role of dung beetles in decomposition
243 and nutrient cycling in tropical ecosystems, it seems likely that the high levels of artificial light and
244 increase in brightness found in Ombrophilous Mixed Forest will affect its functioning.

245 Both Restinga and Mangrove are heavily overlapped by artificial light. Restinga is the
246 terrestrial pioneer vegetation that occurs on sandy shore environments, especially on dunes, and is
247 directly influenced by the sea [33]. Restinga harbours a high diversity of bats [45–47], which are
248 known to be important for the maintenance of forests and to be disturbed by artificial light [48–50].

249 Around the world, mangroves are threatened by deforestation, illegal shrimp culture, expansion of
250 urban areas, tourism, fishing and pollution [51]. Nine percent of the global area of natural or semi
251 natural mangroves has seen an increase in exposure to artificial light [4]. In Brazil this percentage is
252 17% in the same period (Fig 2), with more than 15% of the mangrove area experiencing detectable
253 light (Fig 2). Given that Brazil accounts for approximately 50% of mangroves in South America and
254 7% of the world's mangroves [51], light pollution in these areas should be of particular concern. Both
255 Restinga and Mangrove are coastal ecosystems and the coastal water mass itself is also highly affected
256 by light (Fig 2). Five out of seven extant species of marine turtles in the world nest on the Brazilian
257 coast (*Chelonia mydas*, *Caretta caretta*, *Dermochelys coriacea*, *Eretmochelys imbricata*, and
258 *Lepidochelys olivacea*) - all of them are listed as threatened on the IUCN Red List
259 (<http://www.iucnredlist.org/search>). Artificial lighting disrupts sea turtle hatchling orientation from
260 the nest to the sea [52]. To protect Brazilian coastal ecosystems, the law forbids illumination within
261 50 m of the beach strip between Rio de Janeiro and Rio Grande do Norte States - which corresponds
262 to approximately 2 500 km out of the 7 367 km of Brazilian coast [53]. Due to the scarcity of studies
263 on the consequence of light pollution in these ecosystems, it is not possible to assess if the law is
264 effective.

265 In most developing countries artificial nighttime lighting is relatively recent and concentrated
266 in dense populated urban areas [37]. In contrast, in highly industrialised countries it is much more
267 widespread [1,4], and often considered thus to be a much greater concern. However, our results here
268 highlight that lighting is extensive in some developing countries, including ones with exceptionally
269 high levels of biodiversity. These results also suggest that it is still possible to find vegetation types
270 with natural sky background brightness. Countries in which this is the case have the opportunity to
271 base policies, regulations, and guidelines on minimising rather than mitigating the ecological impacts
272 of artificial nighttime lighting.

273

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277

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